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Fuerst et al.

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(54) **APPARATUS, SYSTEMS, AND METHODS FOR INTRAOPERATIVE VISUALIZATION**

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(52) **U.S. Cl.**
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Primary Examiner — Kyu Chae
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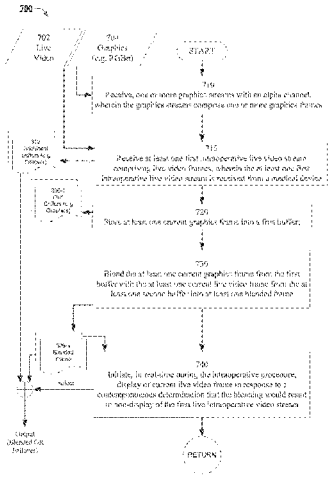
(57) **ABSTRACT**

Errors in a blended stream that would result in non-display or obscuring of a live video stream from a medical device may be automatically detected, and a failover stream corresponding to the first live video stream may be displayed to medical personnel. For example, one or more second input streams that are being blended may contain no data or invalid data which may result in the blended stream not displaying (or obscuring) the live video stream (if the blended were displayed). Switching from blending to a failover buffer may occur within the time to process a single video image frame. Upon detection (prior to display) that the blended stream would not display the live video stream, display of the live video stream from the failover buffer may be initiated. Other aspects are also described and claimed.

20 Claims, 9 Drawing Sheets



(51) **Int. Cl.**

H04N 21/81	(2011.01)
A61B 1/00	(2006.01)
H04N 19/59	(2014.01)
A61B 90/00	(2016.01)

(52) **U.S. Cl.**
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(58) **Field of Classification Search**
CPC H04N 19/59; H04N 21/2187; H04N 21/4312; H04N 21/8146
See application file for complete search history.

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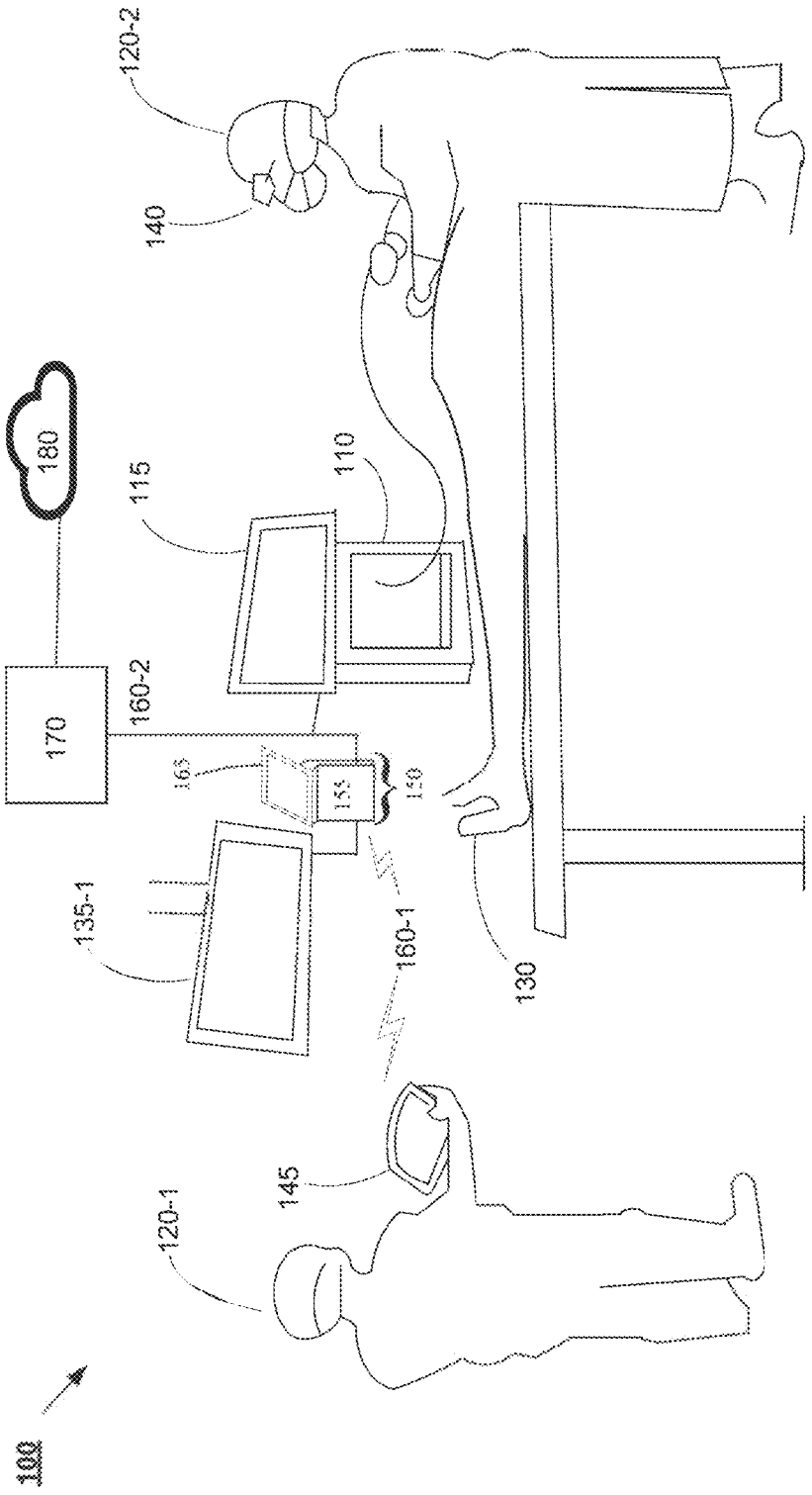
120-2
140
180
115
110
170
160-2
165
155
150
135-1
160-1
130
145
120-1
100

FIG. 1

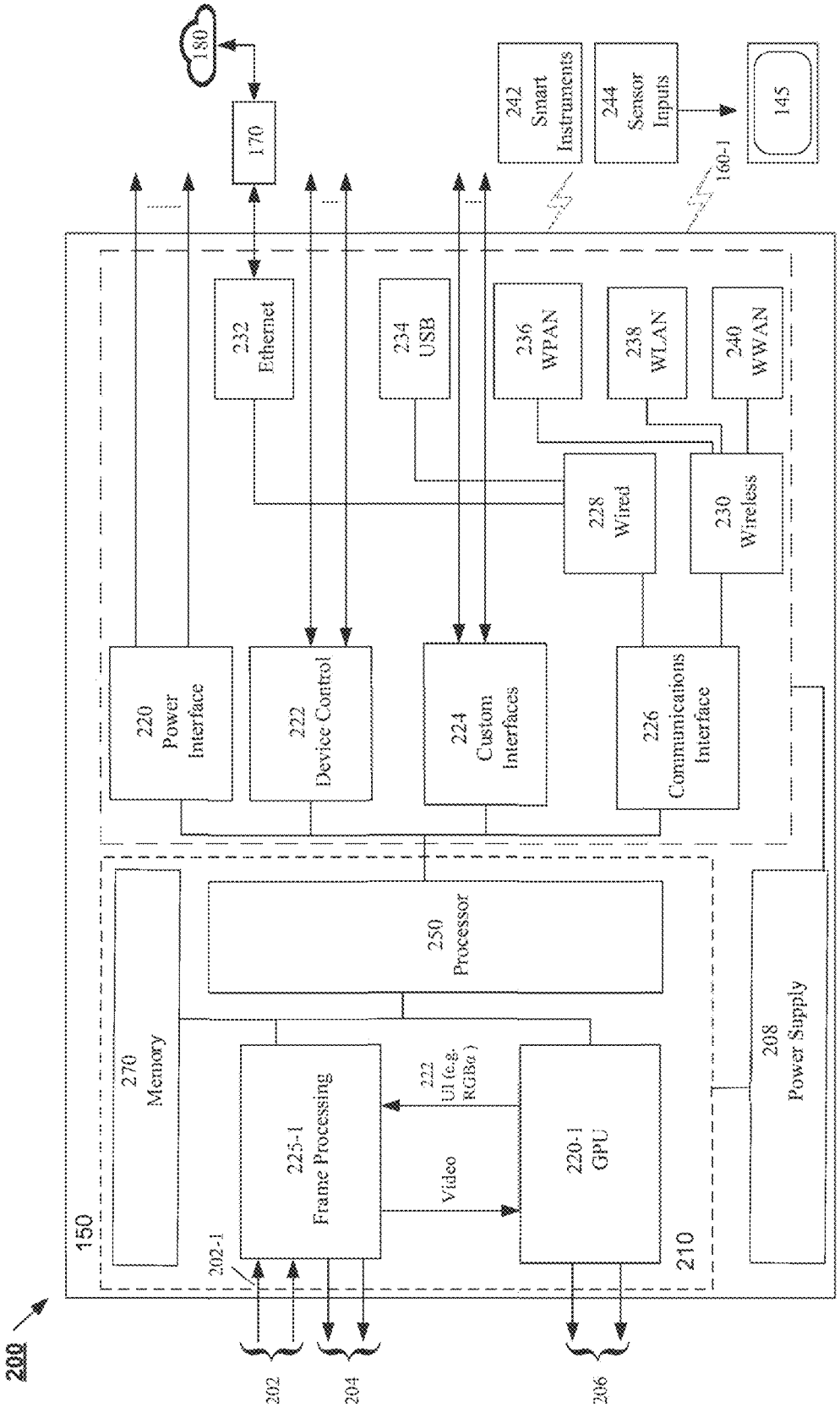
200
150
210
180
170
242 Smart Instruments
244 Sensor Inputs
145
160-1
232 Ethernet
234 USB
236 WPAN
238 WLAN
240 WWAN
228 Wired
230 Wireless
220 Power Interface
222 Device Control
224 Custom Interfaces
226 Communications Interface
250 Processor
270 Memory
208 Power Supply
225-1 Frame Processing
222 UI (e.g. RGBa)
Video
220-1 GPU
202-1
202
204
206

FIG. 2A

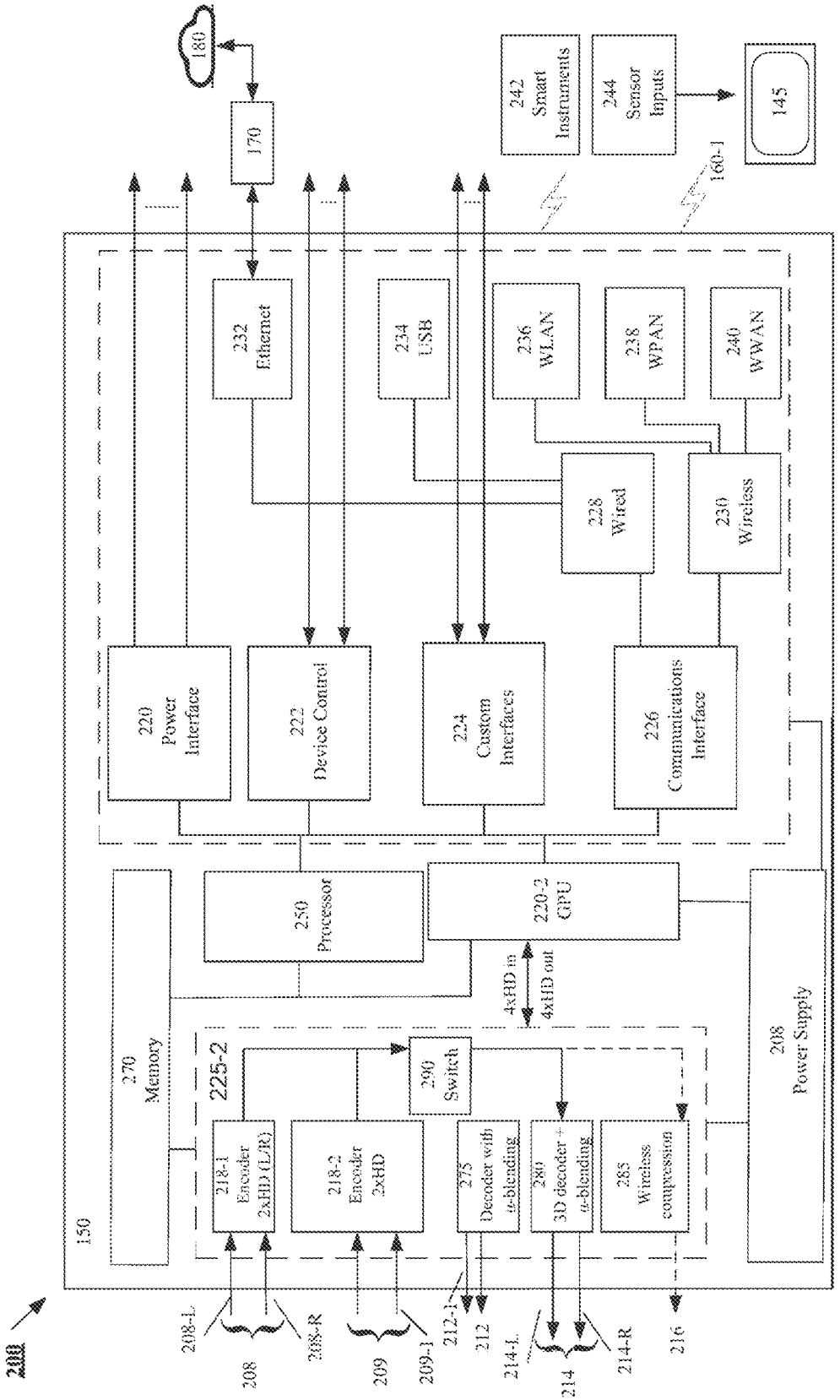
200
150
180
170
242 Smart Instruments
244 Sensor Inputs
145
160-1
232 Ethernet
234 USB
236 WLAN
238 WPAN
240 WWAN
228 Wired
230 Wireless
220 Power Interface
222 Device Control
224 Custom Interfaces
226 Communications Interface
250 Processor
220-2 GPU
4xHD in
4xHD out
270 Memory
225-2
290 Switch
208 Power Supply
218-1 Encoder 2xHD (L/R)
218-2 Encoder 2xHD
275 Decoder with α-blending
280 3D decoder + α-blending
285 Wireless compression
208-L
208
208-R
209
209-1
212-1
212
214-L
214
214-R
216

FIG. 2B

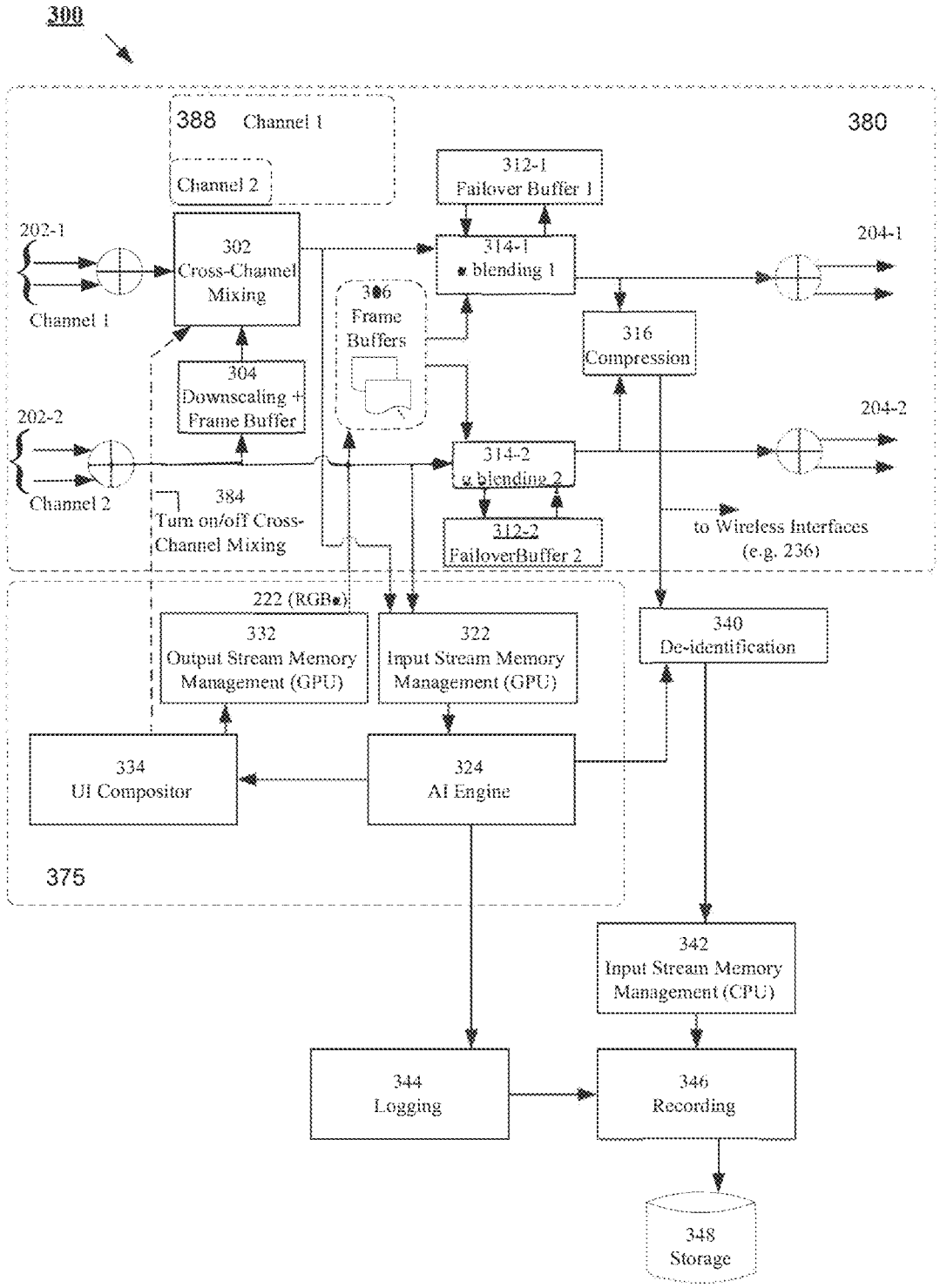
300
380
388 Channel 1
Channel 2
312-1
Failover Buffer 1
202-1
302
Cross-Channel
Mixing
Channel 1
306
Frame
Buffers
314-1
α blending 1
204-1
316
Compression
304
Downscaling +
Frame Buffer
202-2
314-2
α blending 2
204-2
Channel 2
384
Turn on/off Cross-
Channel Mixing
312-2
FailoverBuffer 2
to Wireless Interfaces
(e.g. 236)
222 (RGBα)
332
Output Stream Memory
Management (GPU)
322
Input Stream Memory
Management (GPU)
340
De-identification
334
UI Compositor
324
AI Engine
375
342
Input Stream Memory
Management (CPU)
344
Logging
346
Recording
348
Storage

FIG. 3

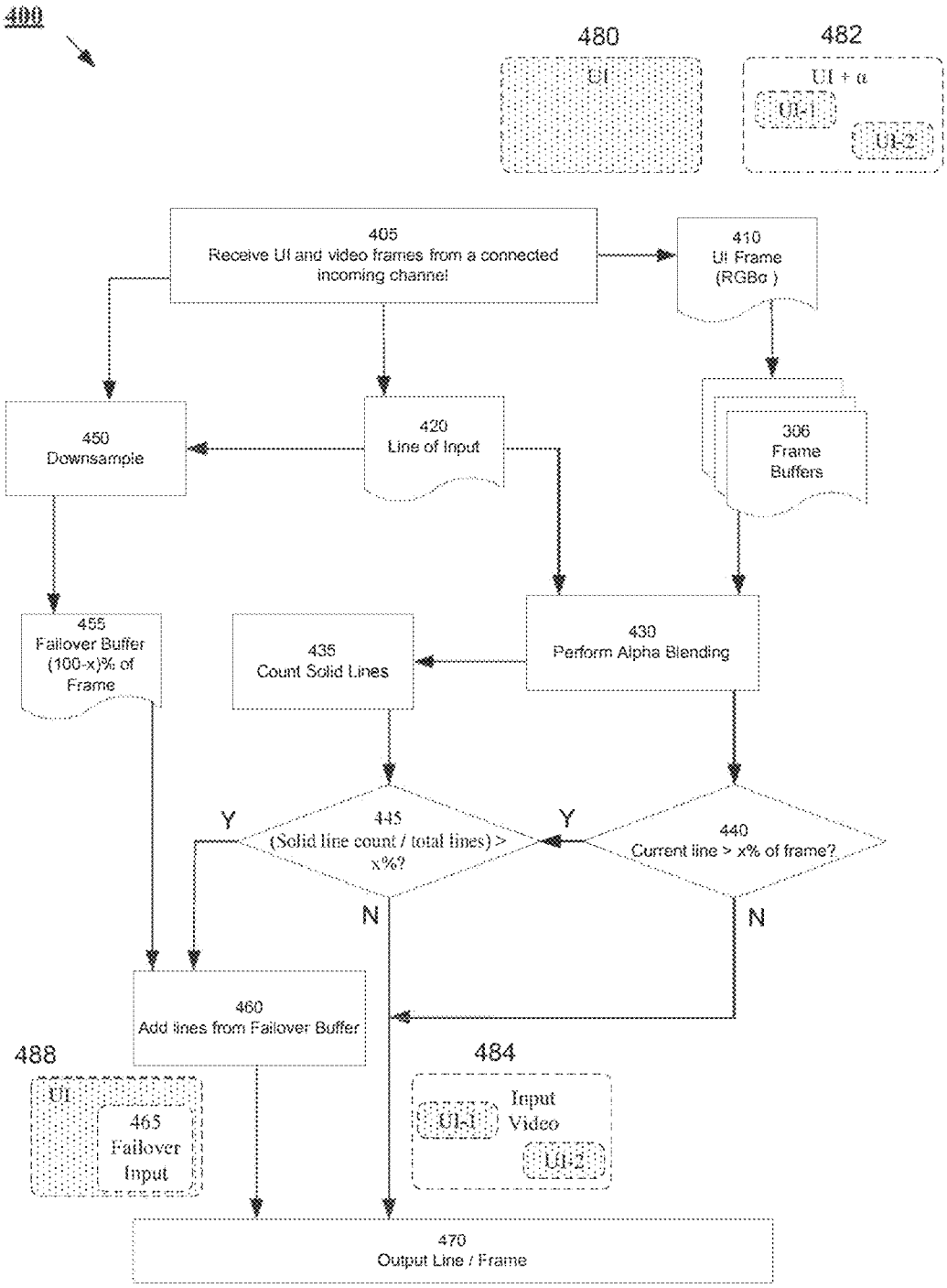
400
480
UI
482
UI + α
UI-1
UI-2
405
Receive UI and video frames from a connected incoming channel
410
UI Frame (RGBα)
450
Downsample
420
Line of Input
306
Frame Buffers
455
Failover Buffer (100-x)% of Frame
435
Count Solid Lines
430
Perform Alpha Blending
Y
445
(Solid line count / total lines) > x%?
Y
440
Current line > x% of frame?
N
N
460
Add lines from Failover Buffer
488
UI
465
Failover Input
484
Input Video
UI-1
UI-2
470
Output Line / Frame

FIG. 4

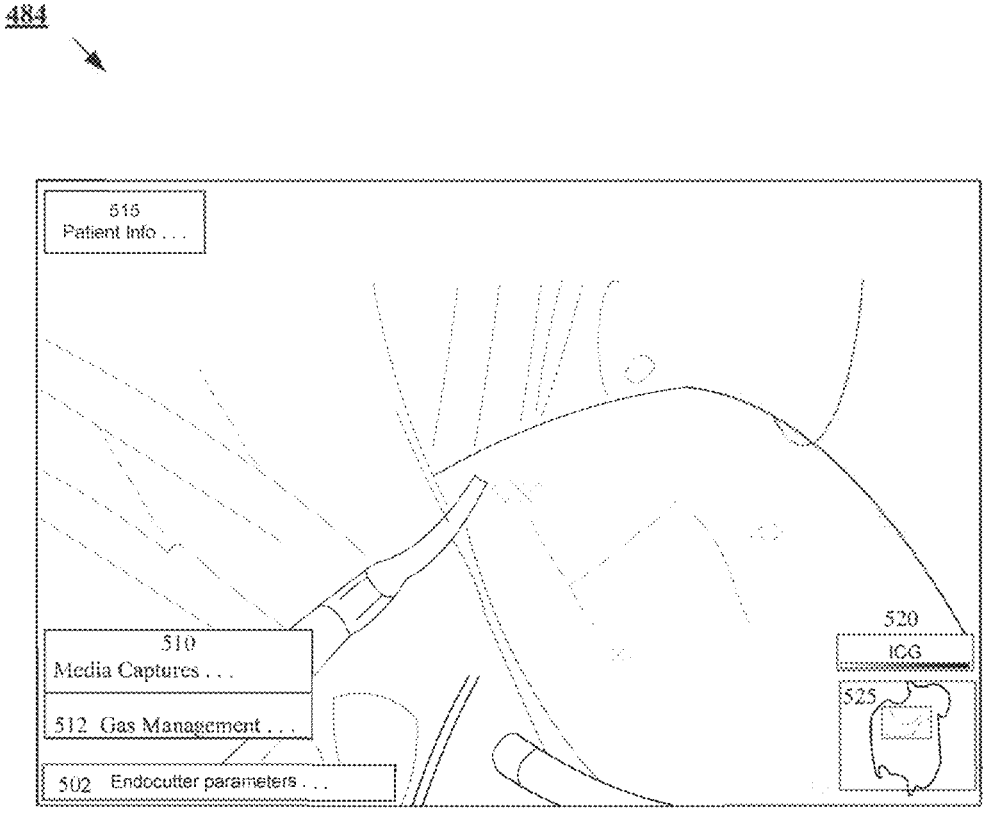
484
515
Patient Info . . .
510
Media Captures . . .
512 Gas Management . . .
502 Endocutter parameters . . .
520
ICG
525

FIG. 5A

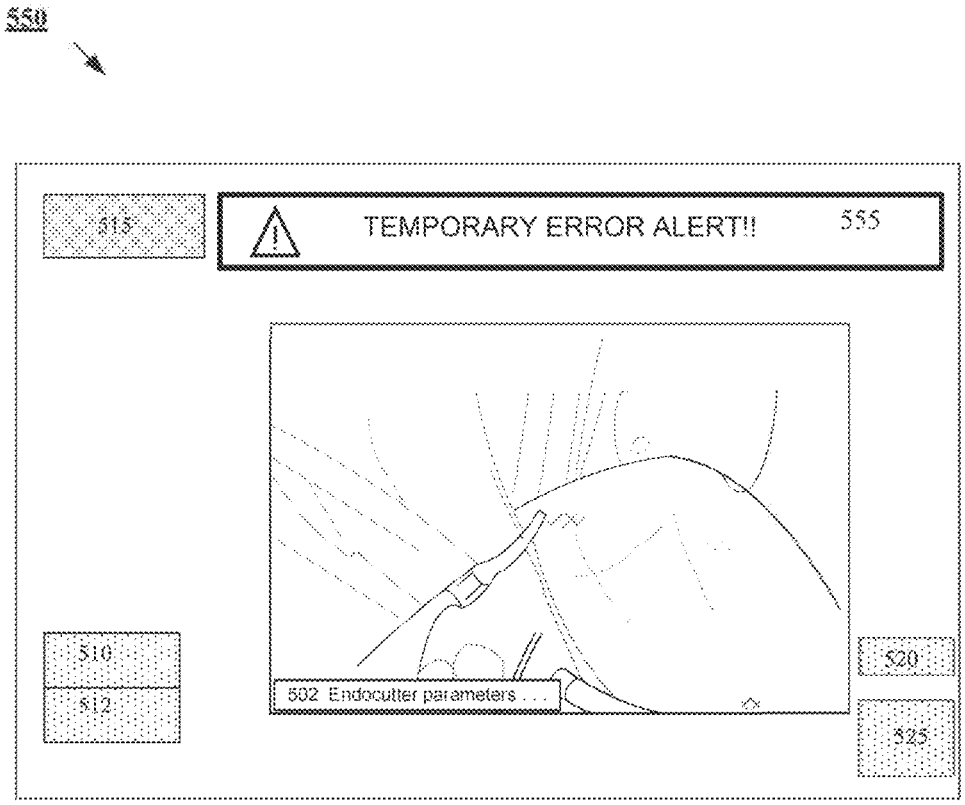
550
515
TEMPORARY ERROR ALERT!!
555
502 Endocutter parameters . . .
510
512
520
525

FIG. 5B

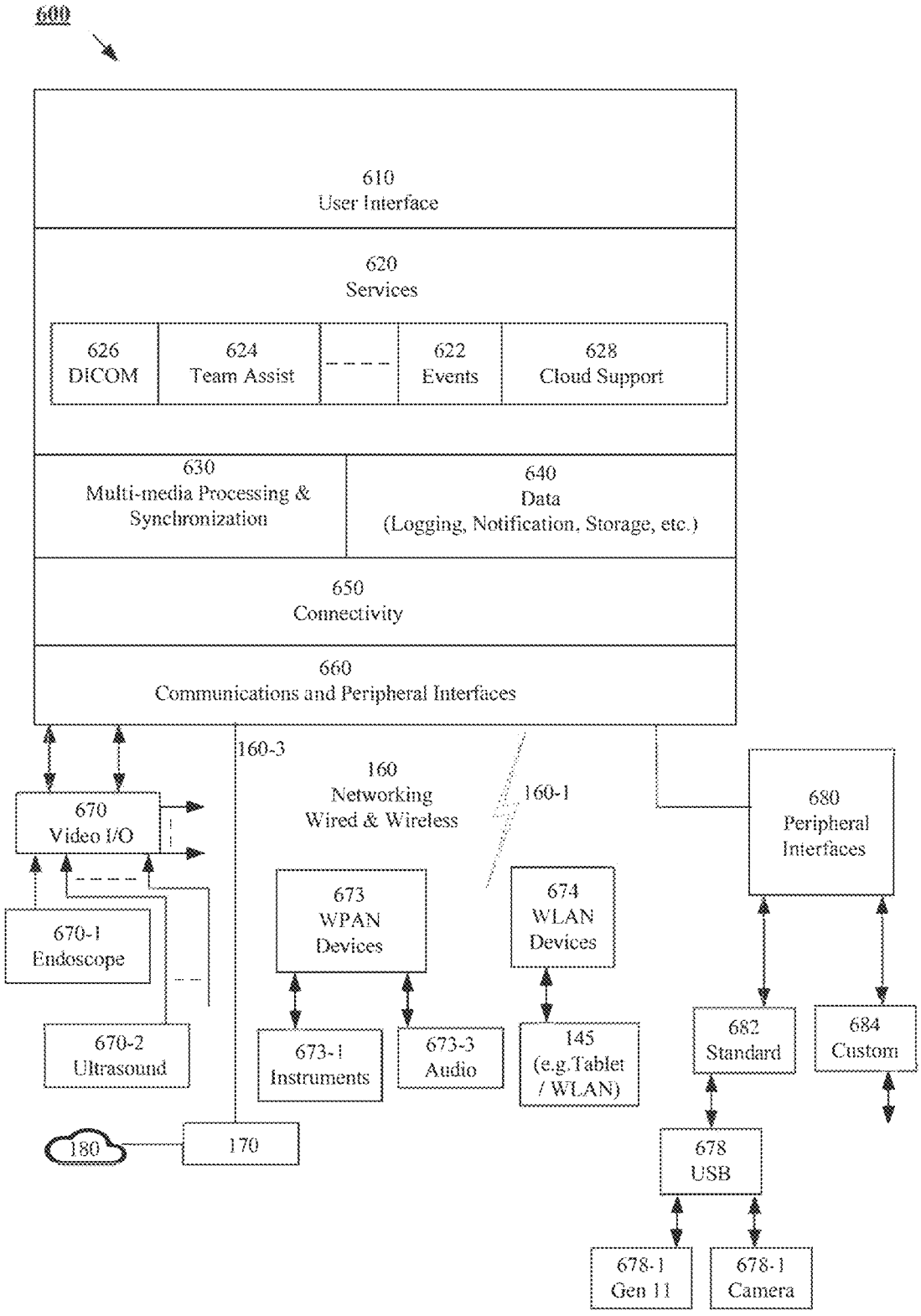
600
610
User Interface
620
Services
626
DICOM
624
Team Assist
622
Events
628
Cloud Support
630
Multi-media Processing & Synchronization
640
Data
(Logging, Notification, Storage, etc.)
650
Connectivity
660
Communications and Peripheral Interfaces
160-3
160
Networking
Wired & Wireless
160-1
680
Peripheral Interfaces
670
Video I/O
670-1
Endoscope
670-2
Ultrasound
673
WPAN
Devices
674
WLAN
Devices
673-1
Instruments
673-3
Audio
145
(e.g.Tablet / WLAN)
682
Standard
684
Custom
678
USB
678-1
Gen 11
678-1
Camera
180
170

FIG. 6

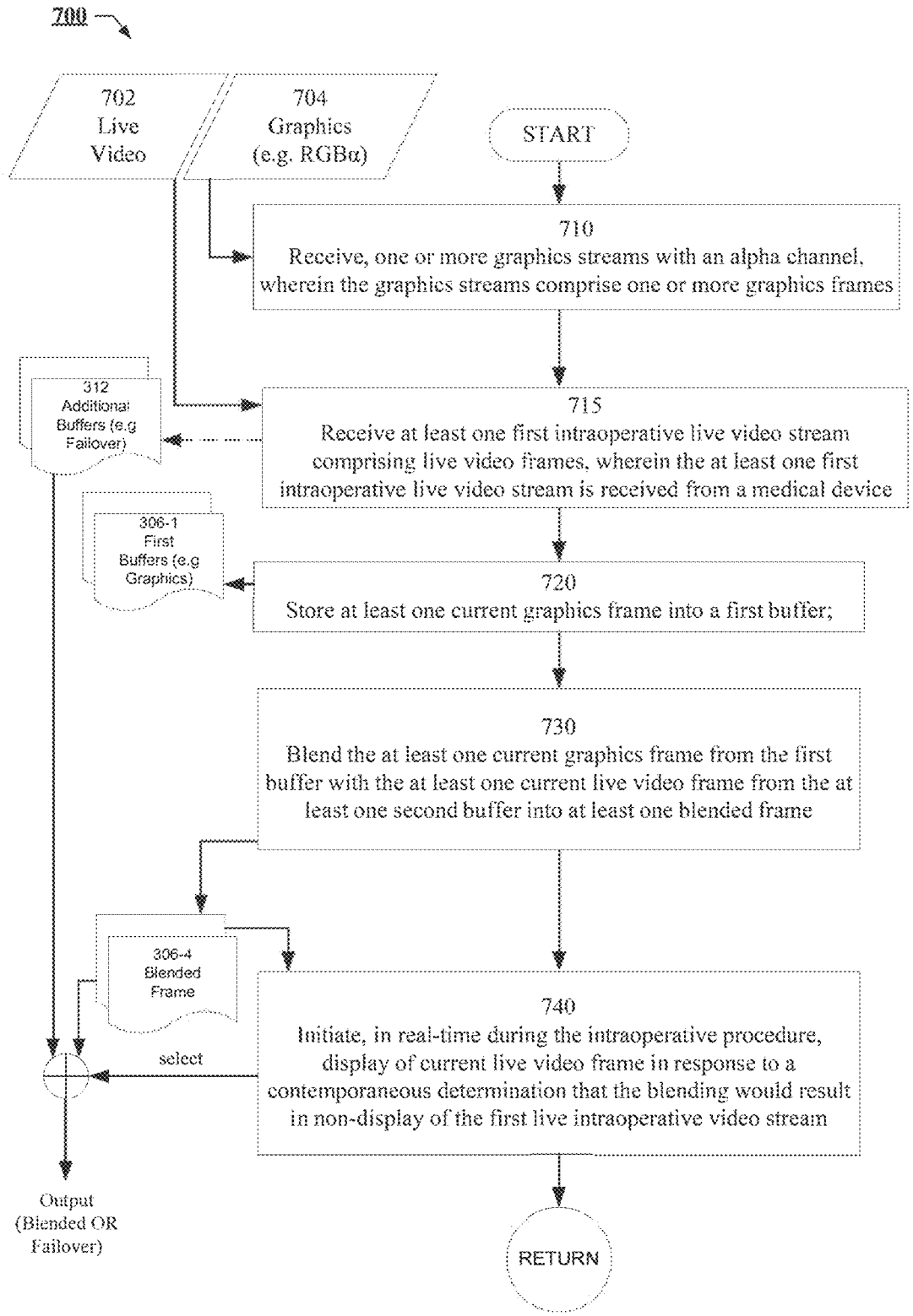
700
702
Live
Video
704
Graphics
(e.g. RGBα)
START
710
Receive, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames
312
Additional
Buffers (e.g
Failover)
715
Receive at least one first intraoperative live video stream comprising live video frames, wherein the at least one first intraoperative live video stream is received from a medical device
306-1
First
Buffers (e.g
Graphics)
720
Store at least one current graphics frame into a first buffer;
730
Blend the at least one current graphics frame from the first buffer with the at least one current live video frame from the at least one second buffer into at least one blended frame
306-4
Blended
Frame
740
Initiate, in real-time during the intraoperative procedure, display of current live video frame in response to a contemporaneous determination that the blending would result in non-display of the first live intraoperative video stream
select
Output
(Blended OR
Failover)
RETURN

FIG. 7

APPARATUS, SYSTEMS, AND METHODS FOR INTRAOPERATIVE VISUALIZATION

This application claims the benefit of U.S. Provisional Patent Application No. 63/256,514, filed on Oct. 15, 2021, which application is incorporated herein by reference.

FIELD

The subject matter disclosed herein relates to intraoperative visualization and specifically to apparatus, systems, and methods that enhance fault tolerance in intraoperative visualization systems.

BACKGROUND

Visualization systems are often used intraoperatively for imaging tissue, performing biopsies, surgery, diagnostic, and/or other medical procedures. The term "intraoperative" as used herein refers to actions performed or events that occur during any medical procedure (invasive or non-invasive). In situations where a visualization system mixes and blends multiple streams, unexpected failures may result in no image being shown to medical personnel. Because visualization is often central to the performance of many medical procedures, failures can detrimentally impact performance of the procedure causing delays, increasing the likelihood of errors, interrupting flow, lowering device utilization, and in some cases could lead to the procedure being aborted. Accordingly, some embodiments disclosed herein enhance safety and efficacy by enhancing fault tolerance in intraoperative visualization systems.

SUMMARY

In some embodiments, a method may comprise: receiving, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames; receiving at least one first intraoperative live video stream comprising live video frames, the at least one first intraoperative live video stream being received from a medical device; storing at least one current graphics frame into a first buffer; blending the at least one current graphics frame from the first buffer with the at least one current live video frame into at least one blended frame; and initiating, in real-time during the intraoperative procedure, display of current live video frame, in response to a contemporaneous determination that the blending would result in non-display of the at least one current live video frame. In some embodiments, the at least one first intraoperative live video stream may be obtained by mixing two intraoperative live video streams. In some embodiments, the at least one first intraoperative live video stream may comprise a stereoscopic live video stream.

In some embodiments, the method above may further comprise displaying, in real time, the at least one current live video frame along with an error indication.

In some embodiments, the determination to initiate display of the current live video frame may occur within the time to complete the blending of the at least one current graphics frame with the at least one current live video frame. In some embodiments, the determination to initiate display of the at least one current live video frame may be based on a ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame. For example, the determination to initiate display of the at least one current live video frame may be made when the ratio exceeds a threshold.

In some embodiments, a display of the at least one blended frame may be initiated, in response to a determination that the blending would result in display of the at least one current live video frame. For example, the determination to initiate display of the at least one blended frame may be made when the ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame does not exceed a threshold.

In some embodiments, receiving at least one first intraoperative live video stream may comprise at least one of: optionally storing the at least one current live video frame into at least one second buffer; or downsampling the at least one current live video frame and storing the at least one downsampled current live video frame into at least one third buffer; or a combination thereof. In some embodiments, the downsampling may be performed in real-time.

In another aspect, an apparatus may comprise: at least one memory, the memory comprising a plurality of buffers, and a processor coupled to the memory wherein the processor is configured to: receive, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames; receive at least one first intraoperative live video stream comprising live video frames, the at least one first intraoperative live video stream being received from a medical device; storing at least one current graphics frame into a first buffer; blend the at least one current graphics frame from the first buffer with the at least one current live video frame into at least one blended frame; and initiate, in real-time during the intraoperative procedure, display of current live video frame, in response to a contemporaneous determination that the blending would result in non-display of the at least one current live video frame. In some embodiments, the at least one first intraoperative live video stream may be obtained by mixing two intraoperative live video streams. In some embodiments, the at least one first intraoperative live video stream may comprise a stereoscopic live video stream. In some embodiments, the apparatus and/or the processor may be configured to perform the methods described above.

In a further aspect, a system may comprise: means for receiving, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames; means for receiving at least one first intraoperative live video stream comprising live video frames, the at least one first intraoperative live video stream being received from a medical device; means for storing at least one current graphics frame into first buffering means; means for blending the at least one current graphics frame from the first buffering means with the at least one current live video frame into at least one blended frame; and means for initiating, in real-time during the intraoperative procedure, display of current live video frame, in response to a contemporaneous determination that output of blending means would result in non-display of the at least one current live video frame. In some embodiments, the robotic medical system may include means to perform the methods described herein.

In a further aspect, a system may comprise: at least one memory, the memory comprising a plurality of buffers, and a processor coupled to the memory wherein the processor is configured to: receive, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames; receive at least one first intraoperative live video stream comprising live video frames, the at

least one first intraoperative live video stream being received from a medical device; storing at least one current graphics frame into a first buffer; blend the at least one current graphics frame from the first buffer with the at least one current live video frame into at least one blended frame; and initiate, in real-time during the intraoperative procedure, display of current live video frame, in response to a contemporaneous determination that the blending would result in non-display of the at least one current live video frame. In some embodiments, the at least one first intraoperative live video stream may be obtained by mixing two intraoperative live video streams. In some embodiments, the at least one first intraoperative live video stream may comprise a stereoscopic live video stream. In some embodiments, the apparatus and/or the processor may be configured to perform the methods described herein.

In some embodiments, a computer-readable medium may comprise instructions to configure a processor to: receive, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames; receive at least one first intraoperative live video stream comprising live video frames, the at least one first intraoperative live video stream being received from a medical device; storing at least one current graphics frame into a first buffer; blend the at least one current graphics frame from the first buffer with the at least one current live video frame into at least one blended frame; and initiate, in real-time during the intraoperative procedure, display of current live video frame, in response to a contemporaneous determination that the blending would result in non-display of the at least one current live video frame. In some embodiments, the at least one first intraoperative live video stream may be obtained by mixing two intraoperative live video streams. In some embodiments, the at least one first intraoperative live video stream may comprise a stereoscopic live video stream. In some embodiments, computer-readable medium may comprise instructions to configure the processor to perform the methods described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be described, by way of example only, with reference to the drawings.

FIG. **1** shows an example diagram illustrating an example system for intraoperative visualization in accordance with certain embodiments disclosed herein.

FIGS. **2**A and **2**B show schematic block diagrams of example embodiments of apparatus to facilitate fault-tolerant intraoperative visualization.

FIG. **3** shows an example diagram showing signal flow between functional blocks of an apparatus to facilitate fault-tolerant intraoperative visualization.

FIG. **4** shows a flowchart of an example method to facilitate fault-tolerant intraoperative visualization with failover functionality

FIGS. **5**A and **5**B show example images illustrating operation of a system to facilitate fault-tolerant intraoperative visualization.

FIG. **6** shows an example software architecture associated with a system for intraoperative visualization in accordance with certain embodiments disclosed herein.

FIG. **7** shows a flowchart of an example method to facilitate fault-tolerant intraoperative visualization in accordance with certain embodiments disclosed herein.

Like reference numbers and symbols in the various figures indicate like elements, in accordance with certain example embodiments. In addition, multiple instances of a functional element may be indicated by following a first number for the element with a letter or with a hyphen and a second number. For example, multiple instances of an element **160** may be indicated as **160-1**, **160-2**, **160-3** etc. When referring to such an element using only the first number, any instance of the element is to be understood (e.g. element **160** in the previous example would refer to elements **160-1**, **160-2**, and/or **160-3**).

DETAILED DESCRIPTION

Some disclosed embodiments pertain to apparatus, systems, and methods to facilitate intraoperative visualization. In some embodiments, inputs from multiple graphics and video streams may be received. The graphics streams may include instrument sensor data, robot information and parameters (e.g. during robot-assisted surgery), information provided by an Artificial Intelligence (AI) engine, which may be based on analysis of stored data (e.g. gathered during prior intraoperative procedures), etc. The information provided by the AI engine may include intraoperative guidance, suggestions, warnings, and/or assistance. In some embodiments, the AI information may be provided in the form of augmentations (e.g. using augmented reality (AR) techniques over an intraoperative video stream). The video streams may include preoperative images, intraoperative medical images, video obtained by a medical device (such as an endoscope) during the intraoperative procedure, and/or video from operating room cameras, graphics associated with a user interface, etc. In some embodiments, one or more of the intraoperative video streams may be blended (e.g. using alpha blending or a-blending) with one or more graphics streams and displayed to medical personnel (e.g. a surgeon) on one or more of a monitor, headset, and/or a portable computing device to facilitate performance of the intraoperative procedure. For clarity, the live video obtained intraoperatively by a medical device (such as the endoscope) being used for performance of a medical procedure is also referred to herein as the first live video stream or first intraoperative live video stream. The terms "composite stream" or "blended stream" are used to refer to result of blending the first live video stream and graphics streams.

In some embodiments, errors in the blended stream that would result in non-display or obscuring of the first live video stream may be automatically detected, and a failover stream corresponding to the first live video input stream may be displayed to medical personnel. For example, one or more second input streams that are being blended may contain no data or invalid data (e.g. due to source errors, non-availability of the source, transmission errors, non-reception, missing or erroneous alpha channel, data errors, other stream issues, etc.), which may result in the blended stream not displaying (or obscuring) the first live video stream (if the blended were displayed).

In some embodiments, the failover stream may be obtained from a failover buffer, which may be configured to store frames, lines, or portions thereof of the first live video input stream. For example, video from an endoscope may be stored in and then automatically and transparently obtained from a failover buffer when a blended stream contain invalid data are detected. Blending may be automatically resumed when the blended stream correctly incorporates the first live video stream. In some embodiments, the switching from blending to the failover buffer may occur within the time to process a single video image frame. In some embodiments, upon detection (prior to display) that the blended stream would not display or obscure the first live input video

stream, display of the first input video input stream (e.g. from a failover buffer) may be initiated and the first live video stream may be displayed by one or more displays.

In conventional schemes, such unexpected failures may result in no image or a blank screen being shown to medical personnel. Because visualization of the first live video input stream is often central to the performance of many medical procedures, such failures are unacceptable and can detrimentally impact performance of the procedure causing delays, increasing the likelihood of errors, interrupting flow, and in some cases, could lead to the procedure being aborted. In addition, because such failures are unpredictable and can result in medical personnel suddenly "flying blind"—medical personnel may shun the use of normally productive equipment and tools. Thus, disclosed embodiments facilitate fault tolerant highly available continuous intraoperative visualization.

FIG. **1** shows an example diagram illustrating an example system for intraoperative visualization in accordance with certain embodiments disclosed herein. FIG. **1** shows patient **130** undergoing a medical procedure involving the use of an endoscope (not shown in FIG. **1**) being operated by surgeon **120-2**.

As shown in FIG. **1**, apparatus **150** (hereinafter referred to as "hub **150**") may receive data streams over network **170** (e.g. also referred to as hospital network **170**), which may be coupled to devices that are local to the medical facility. Hub **150** may take the form of or include functionality of a computing device capable of graphics and video processing. Hub **150** may also receive multimedia streams such as a video stream from the endoscope (not shown in FIG. **1**A) used by medical professional **120-2**, pre-operative images (e.g. from storage or other devices coupled to network **170**), and intra-operative images (e.g. from local imaging devices). Medical professional **120-2** may view the video from the endoscope using headmounted display (HMD) **140**, which may display high-definition (HD) 3-dimensional (3D) or stereoscopic images. In some embodiments, video from the endoscope may be received by Hub **150**, processed, and then transmitted wirelessly to HMD **140**. In some embodiments, the endoscopic (first) input video stream seen by medical professional **120-2** may be blended with one or more second graphics streams such as graphics, AI input, sensor data, etc. based on the configuration of hub **150**. Sensor data may include data from sensors associated with the endoscope or other instruments being used by medical professional **120**, which may provide camera pose, instrument state, and other information. HMD **140** may be custom or a commercially available HMD.

In some embodiments, hub **150** may also receive AI information streams, including decision-support, video annotations (e.g. to mark blood vessels in images to prevent accidental cutting, to detect bleeding, etc.), warnings (e.g. based on current states of tissue and/or of endoscopic devices, etc.). The endoscope may be controlled using endoscopic controller **110**, which may include and/or be coupled to display **115**. In some embodiments, hub **150** may be capable of displaying an augmented view, which may comprise, for example, an endoscopic view augmented with one or more additional overlays, on display **115**. As examples, the overlays may be simple (such as a toolkit for instrument use), or complex (such as a fusion of pre-operative images, which may be displayed in addition to toolkits, etc.)

In some embodiments, hub **150** may include or be coupled to an AI engine, which may perform some AI processing locally. In some embodiments, AI information streams may be received over network **170** and/or from cloud based services **180**. Cloud based services may be hosted on private clouds, public clouds, and/or hybrid public-private clouds. AI functionality may be distributed between hub **150**, computing devices, and other devices on hospital network **170**, and cloud **180**. For example, hub **150** may run models to provide AI based decision-support, video annotations etc., whereas AI related data may be de-identified (e.g. for patient privacy and regulatory reasons) and stored locally and/or on devices coupled to hospital network **170**, while machine learning models may be trained and/or improved using the de-identified collected data using AI related applications provided on cloud **180**.

In some embodiments, as shown in FIG. **1**, example hub **150** may include a touchscreen display **165**, which may be used to present user-interface (UI) to enable medical professional **120** to select input streams, select AI models to run, and configure other functionality such as display of endoscopic images, reception of sensor data, provide power to devices, and/or control instruments and/or devices coupled to hub **150**. In some embodiments, touchscreen **165** may be detachable and capable of being wirelessly coupled to base unit **155** of hub **150**. In some embodiments, touchscreen **165** may form part of a tablet computer and/or other mobile computing device and processing capability may be distributed between base unit **155** and the tablet or mobile computer that houses touchscreen **165**. In some embodiments, base unit **155** may also serve as a docking station for touchscreen **165** and or other tablet computers and/or mobile computing devices.

In some embodiments, hub **150** may serve as a Wireless Access Point (WAP) and broadcast its own local network **160-1**, which may be used by authorized devices (e.g. within the operating room and/or within range). Authorized devices may be connect to hub **150** (serving as a WAP) over network **160-1** and may be communicatively coupled to hub **150** over network **160-1**. Hub centered network **160-1** may insulate various intraoperative devices in the operating room or in proximity to the operating room from wireless network outages, signal reception issues, bandwidth related issues, etc. that may occur in the wireless network provided by the hospital (e.g. hospital network **170**) or medical facility. Thus, hub centered network **160-1** may facilitate increased bandwidth and lower latencies between intraoperative devices that are coupled to hub **150** and improve information sharing including video, images, graphics, and/or other information, while maintaining privacy. For example, hub **150** may receive images from an intraoperative imaging device (e.g. such as a fluoroscopic camera) in the operating room (OR) over network **160-1** and may display the image on display **135-1**. As another example, hub **150** may send graphics and/or user-interface (UI) information for display on tablet computer **145**. Medical professional **120-1** may use the UI remotely to configure hub **150** and/or one or more devices that are coupled to hub **150** over network **160-1**.

FIGS. **2**A and **2**B are schematic block diagrams **200** of an example system illustrating functional components of embodiments of an apparatus (such as example hub **150**) that facilitates fault-tolerant intraoperative visualization.

As shown in FIG. **2**A, frame processing engine (FPE) **255-1** in hub **150** may receive a plurality of input video streams **202** (e.g. High Definition (HD) video streams, for example, from an endoscope or ultrasound device). The input video streams **202** may include a first input video stream **202-1**, which may correspond to a video stream associated with a procedure currently being performed by medical professional **120-1**. The input video streams **202**

may be provided over standard interfaces (e.g. such as High Definition Multimedia Interface (HDMI) or Serial Digital Interface (SDI), etc.) or custom interfaces. HD video may include 10-bit 4K video such as, for example, of resolution 3840×2160 pixels (which is also referred to as 2160p), 1920×1080 pixels (also referred to as 1080p video), and 1280×720 pixels (also referred to as 720p video) with a frame rate of 59.94 and/or 60 image frames per second (fps).

FPE **225-1** may also be capable of output of video streams **204**. In some instances, the number of output channels may mirror the number of input channels and output video streams **204** may mirror the resolution and frame rate of the input video streams **202**. Output video streams **204** may be transmitted over the HDMI and/or SDI interfaces. In some embodiments, output video streams **204** may also be transmitted wirelessly (e.g. over a Wireless Local Area Network (WLAN)) associated with hub **150**. FPE **225-1** may include and/or be coupled to memory **270**. Memory **270** may include a plurality of frame buffers (not shown in FIG. **2**A), which may be used to store graphics frames and/or video frames. Graphics frames may be received with an "alpha" channel (e.g. as Red-Blue-Green-alpha or "RGBα"), which may indicate the degree of transparency associated with each pixel. The alpha channel may be separate or pre-multiplied. Graphics frames (e.g. UIs) may be received from Graphics Processing Unit (GPU) **220-1**. In some embodiments, memory **270** may hold a plurality of frame buffers for each input video stream. In some embodiments, each frame buffer may be configured to be of the same size as the input video stream being processed. Video and graphics information in frame buffers associated with a channel may be blended based on the alpha information (e.g. in the graphics stream) and output by FPE **225-1**.

In some embodiments, errors in the blended stream that would result in non-display or obscuring of the first live video stream **202-1** (e.g. from the endoscope used by medical professional **120-2**) may be automatically detected, and a failover stream corresponding to the first live video input stream may be displayed to medical personnel. For example, one or more second input streams that are being blended may contain no data or invalid data (e.g. due to source errors, non-availability of the source, transmission errors, non-reception, missing or erroneous alpha channel, data errors, other stream issues, etc.), which may result in the blended stream not displaying (or obscuring) the first live video stream (if the blended were to be displayed).

In some embodiments, FPE **225-1** may automatically detect that the blended stream is faulty and, in response to fault detection, may output a failover stream (referred to herein as output stream "**204-*f***") that corresponds to the first live video input stream **202-1**. The detection of the faulty blended stream and the output of the failover stream **204-*f*** may occur within the time to process and output a single frame, so that the transition is seamless. Output stream **204-*f*** may include information to alert medical personnel **120** to the failure of the one or more second input streams. In some embodiments, the failover stream may be obtained from a failover frame buffer (hereinafter "failover buffer"), which may be configured to store frames, lines, or portions thereof of the first live video input stream. For example, first video input **202-1** from the endoscope may be stored in and then automatically and transparently obtained from a failover buffer when the one or more second input streams that contain invalid data are detected. In some embodiments, upon detection (prior to display) that the blended stream would not display the first live input video stream or would obscure the first live input video stream, then display of the first input video input stream (e.g. from a failover buffer) may be initiated and the first live video stream may be displayed by one or more displays. Further, blending may be automatically resumed when the blended stream correctly incorporates the live video stream and FPE **225-1** may then again output a blended video stream **204** (instead of failover stream **204-*f***).

In some embodiments, FPE **225-1** may be implemented using an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) add-on board, and/or using some combination of hardware, software, and firmware. As one example, FPE **225-1** may use FPGAs in an M2 form factor and use the Peripheral Component Express (PCIe) interface to communicate with GPU **220-1** processor **250** and/or other components on hub **150**. PCIe is a high-speed serial computer expansion bus standard. In the embodiment above, FPE **225-1** may be added as a solution to an existing computing platform such as a PC. For example, FPE **225-1** (e.g. as an add-on PCIe component) may be used to add functionality disclosed herein to an existing computing platform that may lack features disclosed herein. In some embodiments, FPE **225-1** and other hub components may receive power from Power Supply **208**, which may be compliant with the IEC **60601-1** standard for medical equipment. IEC **60601-1** is a series of standards related to the basic safety and essential performance requirements of medical electrical equipment.

GPU **220-1** may perform graphics and AI processing. For example, GPU **220-1** may include Tensor Processing Units (TPUs) or tensor cores, which may be capable of running AI models, graphics processing including 3D graphics, video rendering, etc. GPU **220-1** may be able to receive and process video input from FPE **225-1** and pre-operative and intra-operative images related to patient **130**. AI applications running on GPU **220-1** may process the received input to determine and mark blood vessels, bleeding, etc. in frames. In some embodiments, GPU **220-2** may provide graphics and/or Uls and/or augmentations in real-time to FPE **225-1**, which may be provided to medical professionals **120** intra-operatively as decision support, guidance, warnings, etc. using annotations/augmentations to video. GPU **220-1** may also receive video input from FPE **225-1**, which may be displayed along with any augmentations on displays **135-1**, **165** (FIG. **1**) and/or on tablet **145**.

Although shown as separate from FPE **225-1**, functionality associated with one or more of GPU **220-1**, processor **250** and memory **270** may be combined with FPE **225-1** (e.g. as single component, chip, or card), or be external to FPE **225-1**. For example, memory **270** may be distributed across hub **150** so that one or more components such as processor **250**, FPE **225-1**, and/or GPU **220-1** may each include local memory and may also access a main or system memory. Further, memory **270** may include primary and/or secondary memory.

Program code, data, images, configuration information, graphics, image and video frames, models—including AI models, etc. may be stored in memory **270**, and read and/or executed by one or more of FPE **225-1**, GPU **220-1**, and/or processor **250** to perform the techniques disclosed herein. As used herein, the term "memory" refers to any type of long term, short term, volatile, nonvolatile, or other memory and is not to be limited to any particular type of memory or number of memories, or type of media upon which memory is stored. Examples of storage media include computer-readable media encoded with databases, data structures, etc. and computer-readable media encoded with computer programs. Computer-readable media may include physical

computer storage media. A storage medium may be any available medium that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise Random Access Memory (RAM) and variations thereof including Non-Volatile RAM (NVRAM), Read Only Memory (ROM) and variations thereof Erasable Programmable (EPROM), Flash Memory, etc. Computer-readable media may also include Compact Disc ROM (CD-ROM), memory cards, portable drives, or other optical disk storage, magnetic disk storage, solid state drives, other storage devices, or any other medium that can be used to store desired program code in the form of instructions and/or data structures and that can be accessed by a computer; disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and Blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

Communications interface **226** may be capable of wired (e.g. using wired communications interface **228**) or wireless (e.g. using wireless communication interface **230**) communications with another device (e.g. HMD **140**) and may be used to receive sensor inputs **224**, communicate with smart instruments **242**, and/or external networks such as hospital network **170** (FIG. **1**)).

Captured images, AI models, instrument state, sensor input **242**, input from smart instruments **244**, robot data, etc., may be received over communications interface **226**. User input (e.g. received from tablet **145**) may also be received and confirmations/messages transmitted using communications interface **226**. Wireless communication may include communication using one or more of: Wireless Local Area Network (WLAN) interface **238** (e.g. with tablet **145**, display **140**, over Wi-Fi etc.), which may be based on the IEEE 802.11 standards, and/or over Wireless Wide Area Networks (WWAN) interface **240** (e.g. with a remote mobile device, cloud based edge server over cloud **180**, etc.), which may be based on cellular communication standards such as a Fifth Generation (5G) network, or Long Term Evolution (LTE), and/or over Wireless Personal Area Networks (WPAN) interface **236** (e.g. with audio devices, some proximate smart instruments **242**, etc.), which may be based on IEEE 802.11x (e.g. using Bluetooth, etc.).

In some embodiments, cloud based applications, AI models, pre-operative and intra-operative images, etc. may be downloaded by processor using wired interface **228** from one or more devices coupled to hub **150** over USB interface **234**, and/or servers coupled to hospital network **170** over Ethernet **232**, and/or from cloud based servers coupled to cloud **180** over Ethernet **232**.

In some embodiments, processor may also send commands to control devices based on input received from a medical professional **120**, or based on instrument state, sensor input, configuration settings, etc. using device control interface **222** or over communications interface **226**. Power interface **220** may be enabled by processor **150** to supply power to one or more instruments, sensors, and/or other devices coupled to hub **150**. Hub **150** may receive power from power supply **208**, when plugged in and, in some embodiments, may include backup battery power.

Processor **150** may also communicate with devices (e.g. robotic or other devices) over custom interfaces **224**, which may be proprietary. In some embodiments, processor may also run program code to control operation of hub **150**, log events, notify medical personnel (e.g. via messages), store data, images, sensor input, pull up patient records from databases (local or networked), facilitate maintenance of synchronization for multi-media operations, provide support for the Digital Imaging and Communications in Medicine (DICOM) and other standards, facilitate access to cloud based services etc. For example, based on user input and configuration information, processor **150** may log and record a procedure performed using an endoscope for replay (e.g. for training and/or review) and/or analysis (e.g. to train a machine learning/AI model) at a subsequent time. As another example, processor **150** may facilitate the live streaming of the procedure via communications interface **226** (e.g. for educational or training purposes). DICOM is a standard for communication and management of medical imaging information and related data between devices.

The methodologies described herein may be implemented in hardware, firmware, software, or any combination thereof. For a hardware implementation, processor **250**, FPE **225**, GPU **220** may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), image processors, digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, electronic devices, other electronic units designed to perform the functions described herein, or any combination thereof. Processor **250** and GPU **220** may also include functionality perform other well-known computer vision and image processing functions such as feature extraction from images, image comparison, image matching, object recognition and tracking, image compression and decompression, mixing—including line-wise mixing, alpha blending, etc. The components and/or blocks shown in FIGS. **2**A and **2**B (e.g. processor **250**, GPU **225**, FPE **220**, memory **270**, communications interface **226**, etc.) may be coupled using buses, interfaces (e.g. PCIe, etc.), wired connections, etc.

FIG. **2**B is a schematic block diagram **200** of an example system illustrating functional components of another embodiment of an apparatus (such as example hub **150**) that facilitates intraoperative visualization. Components with similar labels function in a manner similar to that described in FIG. **2**A. The description of FIG. **2**B describes an embodiment reflecting some changes in function, behavior, or interaction of functional blocks and/or components relative to FIG. **2**A.

As shown in FIG. **2**B, encoder **218-1** may receive and encode 3D HD video stream **208** (e.g. from a 3D or stereoscopic camera associated with endoscope), which may include a left video channel **208**-L and a right video channel **208**-R each at 60 fps. Further, as shown in FIG. **2**B, encoder **218-2** may receive and encode 2 separate HD streams **209** (e.g. from a C-arm extension camera and an ultrasound device) each at 60 fps. Switch **290** may receive encoded input video streams **208** and **209** as well as graphics input from GPU **220-2** in the form of RGBα streams (an RGB stream with an a channel). As shown in FIG. **2**B, switch **290** may be capable of sending 4 HD input streams each at 60 fps and receiving 4 HD graphics RGBα streams each at 60 fps to/from GPU **220-2**. Switch **290** may be configured to send encoded input stream **208** and RGBα stream to 3D decoder with alpha blending **280**. Similarly, switch **290** may be configured to send encoded input streams **209** and RGBα stream to decoder with alpha blending **275** and/or to compression and wireless transmission block **285**.

In normal operation, for example, when a blended (graphics and video) frame output by 3D decoder with alpha blending **280** frame correctly incorporates input video channels **208**, the blended streams may output as 3D video

stream **214** (e.g. to HMD **140**), which may include a left video channel **214**-L and a right video channel **214**-R each at 60 fps. As another example, when a blended (graphics and video) decoder output by decoder with alpha blending **275** frame correctly incorporates input video channels **209**, the blended streams may output as HD streams **212** each at 60 fps.

In instances when the blended stream is faulty and fails to correctly incorporate input video streams **208** and/or **209**, then, FPE **225-2** may automatically detect the faulty blended stream and, in response to detection of the faulty blended stream, may output a failover stream (referred to herein as output stream "**214**-*f*" or **212**-*f*" that corresponds to the first live video input stream **208** or **209**, respectively).

The faulty blended stream may result from one or more of the second input graphics RGBα streams containing no alpha data or invalid alpha data (e.g. due to source errors, non-availability of the source, transmission errors, non-reception, alpha channel error, data errors, other stream issues, etc.). In the situation described above, the faulty blended stream would result in a black screen and/or in the live input video streams (**208** or **209**) not being displayed—if the blended stream were output and displayed. In the situation described above, FPE **225-2** may automatically detect the faulty blended output stream and, may output a failover stream (referred to herein as output stream "**214**-*f*" or **212**-*f*" that corresponds to the first live video input stream **208** or **209**, respectively). The detection of erroneous second input stream and output of the failover stream may occur within the time to process and output a single frame, so that the transition is seamless. Output streams **214**-*f* or **212**-*f* may include information to alert medical personnel **120** to the failure of the one or more second input streams.

In some embodiments, the failover stream may be obtained from a failover buffer, which may be configured to store frames, lines, or portions thereof of the first live video input stream. A failover buffer may be accessible to each of decoder with alpha blending **275** and 3D decoder with alpha blending **280**. For example, first video input **208** from the endoscope may be stored in and then automatically and transparently obtained from a failover buffer when the one or more second input streams that contain invalid data are detected. Further, blending may be automatically resumed when the one or more second input streams include valid data and FPE **225-2** may then again output a blended video stream **214** (instead of failover stream **214**-*f*).

As shown in FIG. **2**B, FPE **225-2** may also include wireless compression block **285**, which may compress one or more of the input streams for wireless transmission. In FIG. **2**B, for simplicity, stream **216** is shown as being output by wireless compression block **285**. However, stream **216** may be sent to communication interface **226** by wireless compression block **285**, and then output using wireless communication interface **230** and/or WLAN interface **236**.

FIG. **3** shows a schematic block diagram **300** illustrating signal and data flow between functional blocks of an apparatus to facilitate intraoperative visualization such as hub **150**. In some embodiments, blocks **375** and **380** (shown by dashed lines in FIG. **3**) may form part of FPE **225** and GPU **220**, respectively.

As shown in FIG. **3**, in some embodiments, cross channel mixing block **302** may receive first input video stream **202-1** and obtain an appropriately downscaled version of second input video stream **202-2** (e.g. from downscaling+frame buffer **304**) and may mix the two channels to obtain example mixed frame **388**. In some instances, first input video stream and second input video stream may be the left and right channels of a 3D HD video stream (e.g. such video stream **208** in FIG. **2**B). In other instances, first input video stream and second input video stream may be independent video streams received from two different devices (e.g. such as an endoscope and an ultrasound device).

In some embodiments, as shown in FIG. **3**, each input stream (e.g. **202-1**) may be received either over an HDMI and/or SDI interface and the appropriate interface may be selected for input. In some embodiments, second input video stream **202-2** may be downscaled based on mixing parameters and placed in an appropriately sized frame buffer by downscaling and frame buffer block **304**, prior to being input cross channel mixing block **302**. Example mixed frame **388** is shown merely to illustrate a mixed frame. In practice, the appearance of the mixed frame may depend on cross channel mixing parameters Cross-channel mixing may be performed when cross-channel mixing is turned on by cross channel mixing enable signal **384**.

In some embodiments, time stamps associated with the streams **202-1** and **202-2** and other input streams may be synchronized. In some embodiments, the timestamps associated with the input streams may be synchronized using Network Time Protocol (NTP), or Simple Network Time Protocol (SNTP), or by other appropriate methods.

Cross-channel mixing performed by cross-channel mixing block **302** may be turned on or off by cross-channel mixing enable signal **384** from UI compositor block. In instances, where cross-channel mixing is turned off, no cross-channel mixing will be performed by cross-channel performed by cross-channel mixing block **302**. In some embodiments, the output of cross-channel mixing block **302** (e.g. first input video stream **202-1** when cross-channel mixing is turned off or the mixed stream when cross-channel mixing is on) and second input video stream **202-2** may also be received by: (a) input stream memory management block **322**, which may form part of GPU **220**, and (b) alpha-blending block **314-1** (which receives the output of cross-channel mixing block **302**) and alpha-blending block **314-2** (which receives second input video stream **202-2**). In some embodiments, the RGBα stream **222** output by output stream memory management block **332** may be stored in frame buffers **306**. In some embodiments, each stream may have at least two frame buffers, one being written while another is read/processed and logic may switch between the two buffers. In some embodiments, the input video streams **202** may be blended (e.g. by alpha-blending blocks **314**) with the RGBα stream **222**.

In some embodiments, the output of cross-channel mixing block **302** and second input video stream **202-2** may be forwarded by input stream memory management block **322** to AI Engine **324**, which may de-identify the input data in accordance with patient privacy and other data regulations and then run AI models on the input streams to provide decision support, identify features (e.g. blood vessels, bleeding, etc.), make augmentations, provide warnings and/or suggestions, etc. in real-time. The output of AI engine **324** may be provided to User-Interface (UI) compositor block **334**, which may composite the input of AI engine **324** with other UI elements and send the composited UI stream to output stream memory management block **332**, which may output and store RGBα stream **222** (corresponding to the composited UI stream) in frame buffers **306**. The output of AI engine **324** may be logged by logging block **344** and may also be provided to de-identification block **340**, where further de-identification (if appropriate) may occur. De-identification block **340** may provide the de-identified stream along with output video streams to input stream

memory management block **342** (e.g. which may run on or be associated CPU **250**), which may use recording block **346** to record and store the streams in storage **348** along with any logging information provided by logging block **344**.

In some embodiments, alpha-blending block **314-1** (which receives the output of cross-channel mixing block **302**) and alpha-blending block **314-2** (which receives second input video stream **202-2**) may also store the received input streams (e.g. **202**) in failover buffers **312-1** and **312-2**, respectively.

In normal operation, when valid graphics data (with a valid alpha channel) is obtained by alpha-blending block **314-1** and alpha-blending block **314-2** from corresponding frame buffers **306**, then the blended stream output will correctly include the live input video streams (e.g. output of cross-channel mixing block **302** and second input video stream **202-2**) and output as streams **204-1** and **204-2**, respectively. In instances where first input video stream and second input video stream may be the left **208**-L and right **208**-R channels of a 3D HD video stream (e.g. such as video stream **208** in FIG. **2**B) and the output may reflect the input streams in the left **214**-L and right **214**-R channels of blended output 3D HD video stream **214** (in FIG. **2**B) or the left **204**-L and right **214**-R channels of blended output 3D HD video stream **204** (in FIG. **3**). In some embodiments, the streams may be output to HMD **140**.

In instances, when the blended stream is faulty and does not correctly incorporate the input live video streams (e.g. output of cross-channel mixing block **302** and second input video stream **202-2**), then alpha-blending block **314-1** and alpha-blending block **314-2** may: (i) automatically detect that the blended stream contains errors and (ii) may each output a failover stream (e.g. output stream "**204-1***f*" or **204-2***f*" that correspond to the output of cross-channel mixing block **302** and second input stream **202-2**, respectively). As one example, the blended stream may be faulty when one or more of the input graphics RGBα streams **222** that are being blended contain no data or invalid data and/or are missing alpha information (e.g. due to source errors, non-availability of the source, transmission errors, non-reception, missing or bad alpha channel, data errors, other stream issues, etc.). When the faulty graphics RGBα streams **222** are blended, the blended output (if displayed) could result in a black screen and/or the non-display or obscuring of the input live video stream (e.g. non-display or obscuring of the output of cross-channel mixing block **302** and second input video stream **202-2**). In some embodiments, the detection of the faulty blended stream and output of the failover streams **204-1***f* and **204-2***f* may occur within the time to process and output a single frame, so that the transition is seamless. Output streams **204-1***f* and **204-2***f* may include information to alert medical personnel **120** to errors in RGBα streams **222**.

In some embodiments, the failover streams **204-1***f* and **204-2***f* may be obtained from failover buffers **312-1** and **312-2**, respectively, which may be configured to store frames, lines, or portions thereof of the output of cross-channel mixing block **302** and second input stream **202-2**, respectively. Blending may be automatically resumed when the blended stream includes valid data and alpha-blending block **314-1** and alpha-blending block **314-2** may then again output a blended video stream **204** or **214** (instead of failover streams **204-***f* or **214-***f*). The output streams **204-1** and **204-2** may also be received by compression block **316**, where they may be compressed for wireless transmission (e.g. over WLAN interface **236**).

FIG. **4** shows a flowchart of an example method **400** to facilitate intraoperative visualization with failover functionality. In some embodiments, some or all of method **400** may be performed by hub **150**, and/or functional elements of hub **150** such as FPE **225** and/or alpha blending blocks **314** (FIG. **3**), and/or decoder with alpha blending blocks **275** and/or 3D decoder with alpha blending block **280** (FIG. **2**B). Method **400** may be iteratively performed for each incoming frame.

In block **405**, a graphics/UI frame (e.g. a frame from RGBα stream **222**) and a first video frame (e.g. first video frame **202-1**) may be received from a connected incoming channel. As shown in FIG. **4**, the graphics/UI frame may either: (a) include an alpha channel as indicated by example UI (RGBα) frame **482**, or (b) be erroneous, as in example UI frame **480**, where the alpha channel is missing. In some embodiments, the received video frame and UI frame may be stored frame buffers **306**. For example, UI frame **410**, which is shown in FIG. **4** as including an alpha channel may be stored in frame buffers **306**.

In block **430**, alpha blending may be performed using the first or next line **420** of first input video channel (e.g. **202-1**) and a corresponding line in UI frame **410** stored in frame buffers **306**. In some embodiments, perform alpha blending block **430** may detect each solid (e.g. black) line in the current frame and send an indication to count solid lines block **435**.

In some embodiments, count solid lines block **435** may maintain a running count of solid UI frame lines (e.g. solid lines in UI frame **410**) and may increment the number of solid lines each time it receives an indication of detection of a solid line from perform alpha blending block **430**.

In block **440**, if the current line number is not greater than some fraction x of the frame (e.g. less than x % of the frame has been processed), then the blended frame may be maintained as the output, which, when UI frame **410** is valid and includes a correct alpha channel, may appear, upon completion, as example blended frame **484**.

In block **445**, if the solid line count divided by total number of lines in the frame exceeds x % (e.g. solid lines make up more than x % of the frame) ("Y" in block **445**), then block **460** may be invoked. In block **445**, if the solid line count divided by total number of lines in the frame does not exceed x % (e.g. solid lines make up less than x % of the frame) ("N" in block **445**), then the blended frame continues to be output, which, when UI frame **410** is valid and includes a correct alpha channel, may appear, upon completion, as example blended frame **484**.

In block **450**, each line of input may be downsampled (e.g. based on the dimensions of failover buffer **455**) and stored in failover buffer **455**. In some embodiments, failover buffer may be (100−x)% of the frame. As one example, x % may be selected as 66.67% and form $\frac{2}{3}^{rd}$ of the frame, while the failover buffer dimensions may form 33.33% or $\frac{1}{3}^{rd}$ of the frame. The downsampling may occur in real time.

In block **460** (which is invoked when solid lines make up more than x % of the total line count of the frame), the failover buffer is used as shown in example output frame **488**, which includes failover input **465**.

In block **470**, the appropriate frame is output. The output frame may be one of frame **488** (e.g. if the UI frame is determined to have line errors that make up more than x % of the total line count of the frame) or frame **484** (e.g. when UI frame is determined to be valid and line errors do not make up more than x % of the total line count of the frame).

FIGS. **5**A and **5**B show example images illustrating operation of a system to facilitate intraoperative visualization.

FIG. **5**A shows an example (correct) blended frame **484** with first video input from an endoscope (e.g. .video frame **202-1**) showing endoscopic tools such as endoscopic cutter along with current endocutter parameters. Blended frame **500** includes UI input (e.g. which may be provided as RGBα frame **222** by GPU **220** using UI compositor **334** via output stream memory management block **332**). UI input may include one or more sub-windows such as: example patient info sub-window **515**, which may provide information about patient **130** (e.g. retrieved by hub **150** from a server coupled to hospital network **170**); media captures sub-window **510**, which may provide information about the number of available video streams and image streams; gas management sub-window, which may provide information pertaining to parameters such as insufflation pressure, air flow, etc.; map **525**, which provides a higher level indication of the location of the intraoperative procedure within the human body and/or within a portion of the larger anatomy/organ; and Indocyanine Green (ICG) display sub-window, which may allow changing of display modes of a fluoroscopic image; etc.

FIG. **5**B shows the output frame when the bended frame is faulty. For example, the input UI frame **488** may be invalid or erroneous (e.g. because of the absence of alpha channel information or an excess of solid lines relative to the total number of lines in the UI frame), accordingly when blended frame **550** is displayed sub-windows **510**, **512**, **515**, **520**, and **525** do not contain information. However, first video input frame (e.g. **202-1**) that is part of blended frame **550** continues to be displayed using information from the failover buffer (e.g. **312-1** or **455**), thus facilitating continued visualization of the intraoperative procedure. Further, the medical professional (e.g. medical professional **120-2**) is alerted to the temporary failure via the error message displayed in sub-window **555**. In some embodiments, error message sub-window **555** may be placed in in an area not being used to display the first video frame. In some embodiments, the switch from blended frame **500** to blended frame **550** may be seamless and occur in a time less than that to process and output a single blended frame.

FIG. **6** shows an example system **600** illustrating the associated software architecture to support intraoperative visualization in accordance with certain embodiments disclosed herein. In some embodiments, some or all of the software architecture shown in FIG. **6** may be implemented on hub **150**.

As shown in FIG. **6**, software architecture **600** may include communication and peripheral services layer **660** (to support interfacing & communication with external devices), connectivity layer **650** (to enable capture of incoming information and format and package information for output via communication and peripheral services layer **660**), data layer (to enable intraoperative event logging, event notification, and data management including data storage and upload to online web-based portals), multimedia processing and synchronization layer

UI layer **610**, which may allow users to authorize connection of one or more devices, configure coupled devices, select streams, select AI models to run, select pre-operative and intra-operative image sources, configure procedure guidance (e.g. to be provided to medical professionals **120** and/or support staff), specify notifications (e.g. to be provided to personnel upon the occurrence of certain events), configure telementoring, etc.

Services layer **620**, which may be modular, may provide capability to enable advanced applications including AI based applications to be used in an intraoperative setting. For example, services layer **620** may provide: (a) DICOM services functionality **626**, which may catalog and list available sources for relevant preoperative images and may retrieve and store selected images locally.

Services layer **620** may also provide (b) team assist services functionality, which may catalog and list available AI models for selection and running on live input video streams (e.g. to identify and mark blood vessels, etc.); (c) event services functionality **622**, which may record and log events; (d) cloud support services, which may allow access to cloud based applications, models, data service providers, etc. and also allow uploading of data for training AI models, etc. Services layer **620** may also provide various other functionality such as a UI services functionality, which may allow interaction between UI layer and services.

In some embodiments, team assist services **624** may facilitate staff guidance to setup procedure guides tor specific procedures preoperatively and then use these guides intraoperatively to follow steps outlined in the guide. Machine Learning models may be trained offline based on recorded video and procedure setup for specific procedures to automatically recognize phases and steps outlined as part of the procedure. In some embodiments, the trained models may then process live endoscope video feed in real time to automatically recognize steps and phases and auto-advance an on-screen guide to the next step in a procedure guide by changing content.

Team assist services **624** may further include notification related services to facilitate messaging from within the operating room (OR) to personnel outside the OR based on the current status of a procedure. Messages may include one or more notifications such as: a procedure has started, a procedure is likely to complete or go past the scheduled time, an OR is ready, etc. Such notifications may help with planning and more effective use of resources.

In some embodiments, team assist services **624** may include image viewing and image based planning functionality, which may facilitate processing, review, analysis, communication, and media interchange of multi-dimensional digital images acquired pre-operatively (e.g. from Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Diagnostic Ultrasound, X-Ray, Positron Emission Tomography (PET) scans etc.) from imaging devices. Image viewer and image based planning may also facilitate preoperative surgical planning, and the intraoperative display of digital images by enabling 3D rendering and visualization and picture archiving and communication system (PACS) integration. In some embodiments, image viewing and image based planning functionality may also make the above information available over a network or over the web to authorized personnel and facilitate deployment of an online Digital Surgical Portal.

Integrated anatomy, 3D modeling, & patient outcome simulation functionality provided by team assist services **624** may use available pre-operative and intraoperative 3D models and facilitate display and manipulation of the 3D models for pre-operative planning and intra-operative reference and may improve visualization of anatomy and tumors and facilitate performance of patient-specific and procedure-specific simulation.

Multimedia processing and synchronization layer **630** may facilitate management and synchronization of connected input devices, enable data, video, and audio fusion and processing, and also provide services for data management (storage, retrieval, labeling, indexing, etc.)

Data layer **640** may facilitate scalable multi-service and device communication, provide notifications to all stake-

holders related to intraoperative workflow, and facilitate systematic logging and storage of intraoperative information over hospital network **170** and/or through a cloud based data service provider.

Connectivity layer **650** may include functionality to facilitate multimedia data exchange and capture multimedia input received in various formats and over a variety of hardware interfaces such as video, audio, custom interfaces, and may also output information to connected displays as well as to tablet **145**.

Communication and peripheral interface layer **660** may include software to configure and manage WLAN (e.g. Wi-Fi), WPAN (e.g. Bluetooth), WWAN (e.g. 5G), Ethernet, USB, custom peripheral port connectivity, etc.

As shown in FIG. **6**, Communication and peripheral interface layer **660** may facilitate interaction with a variety of external devices and peripherals. For example, video inputs and outputs **670** may use the HDMI and/or SDI interfaces to receive video from devices such as endoscope **670-1**, ultrasound **670-2**, etc. Video inputs and outputs **670** may also output video to external displays **135** (not shown in FIG. **6**).

Wired and wireless networking interface **160** may include wired network connections such as Ethernet connection **160-3**, which may be used to: connect to servers, storage, services etc. on hospital network **170**; facilitate data exchange with the digital surgical portal; and may provide connectivity to cloud based storage and/or services **180**. Wireless network **160-1** may include interfaces for WLAN connections with external WLAN devices **174** such as tablet **145**, which may allow users to interact with, configure, and manage system **600**. In some embodiments, a local (e.g. operating room) wireless network **160** may be provided by hub **150**, which may be used by authorized devices with access to the network to communicate with hub **150** and/or among themselves (e.g. improving bandwidth, latency, and decreasing reliance on the hospital network). Wireless network **160-1** may include interfaces for WPAN connections and communication with external WPAN (e.g. Bluetooth) devices such as audio devices, smart instruments, robotic instruments, sensors, etc.

Peripheral interfaces **680** may include standard interfaces such as USB, which may provide connectivity to OR cameras, provide power, and support surgical instruments such as surgical shears, sealers, etc. Custom interfaces **683** may include interfaces specific to a manufacturer such as for insufflation devices, couplings for electro-mechanical devices such as pumps, aspirators, irrigators, etc.(not shown in FIG. **6**).

FIG. **7** shows an exemplary flowchart of a method **700** for fault-tolerant intraoperative visualization. In some embodiments, method **700** may be performed on a computing device (such as hub **150**). In some embodiments, method **700** may be performed by some combination FPE **225**, GPU **220**, and/or processor **250**. Method **700** may be implemented by some combination of hardware, software, and firmware. As one non-limiting example, method **700** may be implemented using an add-on M2 expansion card with a PCIe interface to add fault-tolerant intraoperative visualization functionality an existing intraoperative computing device.

In block **710**, one or more graphics streams **704**, which include an alpha channel, may be received. The graphics streams **704** may comprise one or more graphics frames. In some embodiments, the one or more graphics streams may include a pre-multiplied alpha channel.

In block **715**, at least one first intraoperative live video stream **702** comprising live video frames may be received, wherein the at least one first intraoperative live video stream **702** may be received from a medical device (e.g. endoscope **670-1**, ultrasound **670-2**, etc. during a medical procedure). As one example, live video stream **702** may be one of live video streams **208** and/or **209** and graphics stream **704** may correspond to graphics (UI) stream **222**. In some embodiments, the at least one first intraoperative live video stream **702** may be obtained by mixing two intraoperative live video streams (e.g. **202-1** and **202-2**). For example, cross-channel mixing may be used to obtain the at least one first intraoperative live video stream. In some embodiments, the at least one first intraoperative live video stream **702** may comprise a stereoscopic live video stream (e.g. 3D live video stream **208**).

In block **720**, at least one current graphics frame may be stored into a first buffer (e.g. frame buffers **306-1**).

In block **730**, the at least one current graphics frame from the first buffer (e.g. **306-1**) may be blended with the at least one current live video frame from the at least one second buffer (e.g. **306-2**) to obtain at least one blended frame. In some embodiments, the blending may be performed in real-time and the output may be stored in blended frame buffers **306-4**. In some embodiments, blending operations may be performed in parallel using multiple processors or processing cores.

In block **740**, display of current live video frame from the at least one additional buffer (e.g. failover buffers **312**) may be initiated in real-time and during the intraoperative procedure, in response to a contemporaneous determination that the blending would result in non-display of the first live intraoperative video stream. For example, upon determining that the blending would result in the current live video being obscured or not being visible, the display of current live video frame from the failover buffers **312** may be enabled. In some embodiments, the determination to initiate display of the current live video frame from the at least one third buffer may occur within the time to complete the blending of the at least one current graphics frame with the at least one current live video frame.

In some embodiments, the at least one current live video frame may be stored into at least one second buffer and at least one third buffer (e.g. failover buffers **312**). In some embodiments, the at least one current live video frame may be downsampled and the at least one downsampled current live video frame may be stored in to the at least one third buffer. In some embodiments, the downsampling may be performed in real-time.

In some embodiments, in block **740**, the determination to initiate display of the at least one current live video frame from the at least one third buffer may be based on a ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame. For example, the determination to initiate display of the at least one current live video frame from the at least one third buffer may be made when the ratio exceeds a threshold.

In some embodiments, the method may further comprise displaying, in real time, the at least one current live video frame from the at least one third buffer along with an error indication (e.g. error indication **555**).

In some embodiments, method **700** may further comprise (e.g. after block **740**) initiating display of the at least one blended frame, in response to a determination that the blending would result in display of the at least one first live intraoperative video stream. For example, in some embodiments, display of the at least one blended frame may be a "default" mode so that the blended frame is displayed when display of the live video stream is not impaired. In instances

where blending would result in the current live video being obscured or not being visible (e.g. as determined in block **740**), the display of current live video frame from the failover buffers **312** may be enabled. For example, the determination to initiate display of the at least one blended frame may be made when the ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame is below a threshold.

Although the present disclosure is described in connection with specific embodiments for instructional purposes, the disclosure is not limited thereto. Various adaptations and modifications may be made to the disclosure without departing from the scope. Therefore, the spirit and scope of the appended claims should not be limited to the foregoing description.

What is claimed is:

1. A processor-implemented method comprising:

receiving, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames;

receiving at least one first intraoperative live video stream during an intraoperative procedure, the first intraoperative live video stream comprising a plurality of live video frames, the at least one first intraoperative live video stream being received from a medical device;

storing at least one current graphics frame into a first buffer;

blending the at least one current graphics frame from the first buffer with at least one current live video frame of the plurality of live video frames into at least one blended frame; and

initiating, in real-time during the intraoperative procedure, display of the at least one current live video frame, in response to a contemporaneous determination that the blending would result in non-display of the at least one current live video frame.

2. The method of claim **1**, wherein the determination to initiate display of the current live video frame occurs within the time to complete the blending of the at least one current graphics frame with the at least one current live video frame.

3. The method of claim **1**, further comprising:

displaying, in real time, the at least one current live video frame along with an error indication.

4. The method of claim **1**, wherein the determination to initiate display of the at least one current live video frame is based on a ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame.

5. The method of claim **4**, wherein the determination to initiate display of the at least one current live video frame is made when the ratio exceeds a threshold.

6. The method of claim **1**, further comprising:

initiating display of the at least one blended frame, in response to a determination that the blending would result in display of the at least one current live video frame.

7. The method of claim **6**, wherein the determination to initiate display of the at least one blended frame is made when a ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame does not exceed a threshold.

8. The method of claim **1**, wherein receiving at least one first intraoperative live video stream comprises at least one of:

optionally storing the at least one current live video frame into at least one second buffer; or

downsampling the at least one current live video frame and storing the at least one downsampled current live video frame into at least one third buffer; or

a combination thereof.

9. The method of claim **8**, wherein the downsampling is performed in real-time.

10. The method of claim **1**, wherein the at least one first intraoperative live video stream is obtained by mixing two intraoperative live video streams.

11. The method of claim **1**, wherein the at least one first intraoperative live video stream comprises a stereoscopic live video stream.

12. The method of claim **1** performed by a processor, wherein the processor is coupled to memory in which a plurality of buffers including the first buffer are implemented.

13. A system comprising:

a video interface to receive at least one first intraoperative live video stream from a medical device during an intraoperative procedure, wherein the at least one first intraoperative live video stream comprises a plurality of live video frames;

a graphics interface to receive, one or more graphics streams with an alpha channel, wherein the graphics streams comprise one or more graphics frames;

a storage comprising a plurality of buffers; and

a processor configured to

store at least one current graphics frame, of the one or more graphics frames, into a first buffer of the plurality of buffers;

blend the at least one current graphics frame from the first buffer with at least one current live video frame of the plurality of live video frames into at least one blended frame, and

initiating, in real-time during the intraoperative procedure, display of the at least one current live video frame, in response to a determination that the blending would result in non-display of the at least one current live video frame.

14. The system of claim **13**, wherein a determination to initiate display of the at least one current live video frame occurs within the time to complete the blending of the at least one current graphics frame with the at least one current live video frame.

15. The system of claim **13**, further comprising the processor causing the display of the at least one current live video frame along with an error indication.

16. The system of claim **13**, wherein a determination to initiate display of the at least one current live video frame is based on a ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame.

17. The system of claim **16**, wherein the determination to initiate display of the at least one current live video frame is made when the ratio exceeds a threshold.

18. The system of claim **13**, wherein the processor is further configured to

initiate display of the at least one blended frame, in response to a determination that the blending would result in display of the at least one current live video frame.

19. The system of claim **18**, wherein the determination to initiate display of the at least one blended frame is made when a ratio of a number of solid lines in the at least one blended frame to a total number of lines in the at least one blended frame does not exceed a threshold.

20. A non-transitory computer-readable medium comprising instructions to configure a processor to

receive a graphics stream that comprises a plurality of graphics frames;

receive an intraoperative live video stream comprising a plurality of live video frames from a medical device during an intraoperative procedure;

store a current graphics frame from the graphics stream into a buffer;

blend the current graphics frame from the buffer with a current live video frame of the intraoperative live video stream, into a blended frame; and

initiate in real-time during the intraoperative procedure, display of the current live video frame, in response to a contemporaneous determination that the blending would result in non-display of the current live video frame.

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